EXHIBIT A:

CONVERTED-WAVE PRESTACK IMAGING AND VELOCITY ANALYSIS BY PSEUDO-OFFSET MIGRATION

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Summary

A new technique for converted-wave (C-wave) prestack imaging and velocity analysis is presented. This technique, called pseudo-offset migration (POM), differs from equivalent-offset migration (EOM) (Bancroft et al., 1998) in how the migration mapping offset is defined. In this paper, we show that POM is less dependent on the initial velocity than EOM and can produce better images and C-wave velocities than P-S DMO plus poststack migration.

Introduction

Converted-wave processing is more difficult than pure-mode processing. A simple common-conversion-point stack requires an input trace to be grouped to different conversion-point positions. Velocity analysis becomes problematic even for a plane-layered medium. Migration is so critically dependent on both P-wave and S-wave velocities that a robust, efficient, and easy-to-use prestack migration method is needed for the C-wave processing.

Equivalent-offset migration (EOM) is a prestack time migration method proposed by Bancroft et al. (1998). EOM performs prestack migration in two steps. The first step is the migration mapping. It maps each input sample to a common-scatter-point and accumulates it at an equivalent-offset (Figure 1). The equivalent-offset (h_e) is defined as a distance between the common-scatter-point (I) and a location of a collocated model-source (S_e) and model-receiver (R_e) so the travel time from the model-source to the model-receiver equals to the input travel time from the source (S) to the receiver (R). The second step is the migration stack, which completes the migration by summing the common-scatter-point gather or EOM gather along the normal-moveout travel times. EOM is claimed to be computationally efficient and weakly velocity-dependent. However, in C-wave processing, P-S EOM (Wang et al, 1996) depends on the initial velocity even for a single constant-velocity flat layer. A new scheme of migration mapping is proposed in this paper. We show that this new technique, called pseudo-offset migration (POM), is less velocity-dependent than EOM and produces better images than P-S DMO plus poststack migration (Harrison, 1992).

Pseudo-offset migration

A pseudo-source (S_p) and a pseudo-receiver (R_p) are defined in Figure 2 such that the following two conditions are satisfied. 1) The total travel time from S_p to D and from D to R_p equals to the total travel time from S to D and from D to R. 2) The ray from S_p to D has a common ray parameter p as the ray from D to R_p. The distance x between S_p and

R_p is called the pseudo-offset. Unlike EOM, POM maps the input geometry to a new geometry defined by the pseudo-offset. After the migration mapping, the migration stack or the C-wave velocity analysis can be performed on POM gathers based on the travel time from S_p to R_p. The travel time is exactly the same as the C-wave reflection travel time for the plane-layered media, which can be approximated by a high-order equation controlled by the C-wave RMS velocity (Thomsen, 1999). POM further distinguishes from EOM in that the pseudo-source and the pseudo-receiver can not be collocated together for C-waves because for the collocated source and receiver the C-wave ray parameters (p_{ep} and p_{es} in Figure 1) are not constant. C-wave velocity analysis using POM is independent of migration input velocities for the plane-layered media, but EOM is not. For dipping layers, POM mapping is dependent on the input velocities. However, C-wave velocity analysis becomes much easier after POM because the positions of dipping events are close to their true conversion-point positions.

Figure 3 shows the velocity sensitivity test for both POM and EOM. All the gathers are moveout corrected with the correct model velocity. The model is a single layer with the constant C-wave velocity at 2121 m/s and the velocity ratio $\gamma_0 = 2$. Figure 3a shows that if the input parameters are correct, both POM and EOM gather can be flattened with the model parameters. However, if the C-wave input velocity is wrong and even if γ_0 is still correct, EOM gather no longer has correct velocity information. The gathers in Figure 3b are generated with an incorrect input velocity. Figure 3b shows that correcting the EOM gather using the model velocity can not flatten the gather. This indicates that the new velocity picked from the EOM gather depends on the input velocity. The POM gather shown in Figure 3b can be flattened with the model velocity. This indicates that the new velocity analysis of the POM gather does yield the correct velocity and it is independent of the input velocity. Even if both the input velocity and γ_0 may go wrong, figure 3c shows the POM gather is less affected by the input parameters, but the EOM gather can no longer preserve the model velocity.

Figure 4c shows a field data example of C-wave prestack time migration using POM. Comparing with P-S DMO plus poststack migration (Figure 4a), Figure 4c is well focused around the salt dome. Figure 4b shows a C-wave velocity spectrum after P-S DMO at the location A marked on Figure 4a. Figure 4d is the corresponding velocity spectrum after POM. Velocity analysis is much easier using Figure 4d than Figure 4b since the energy is well focused and is at the migrated position after POM.

Conclusions

POM is presented for C-wave prestack imaging. It is less sensitive to the velocity error than EOM. C-wave velocity analysis using POM is much easier than that using P-S DMO. POM is a useful technique for prestack time migration and velocity analysis.

Acknowledgements

We would like to thank Conoco and PGS for permission to publish the results.

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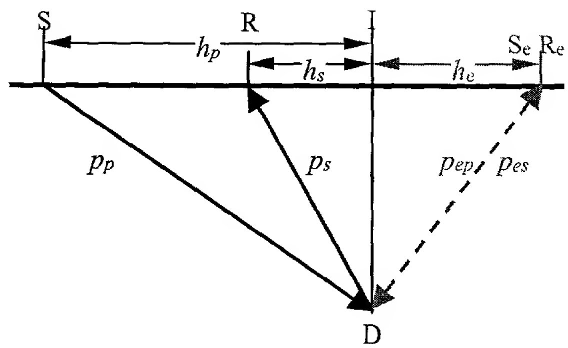

Fig. 1. Geometry of equivalent-offset h_e

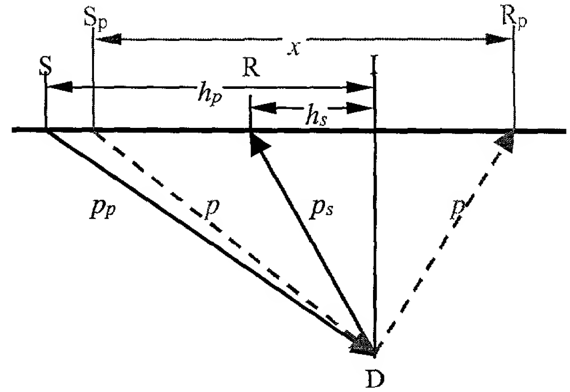

Fig. 2. Geometry of pseudo-offset x

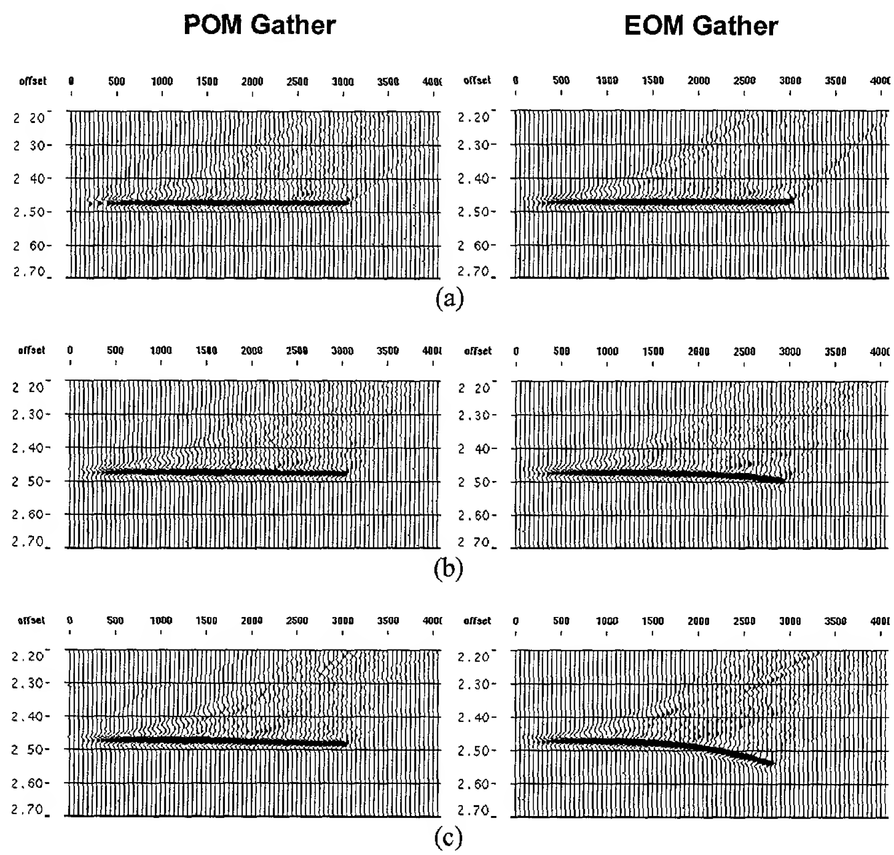

Fig. 3. Moveout corrected POM and EOM gathers. The model has the C-wave velocity at 2121 m/s and γ_0 at 2. The input parameters used for migration mapping are (a) C-wave velocity 2121 m/s and γ_0 2, (b) C-wave velocity 1500 m/s and γ_0 2, and (c) C-wave velocity 1500 m/s and γ_0 3.

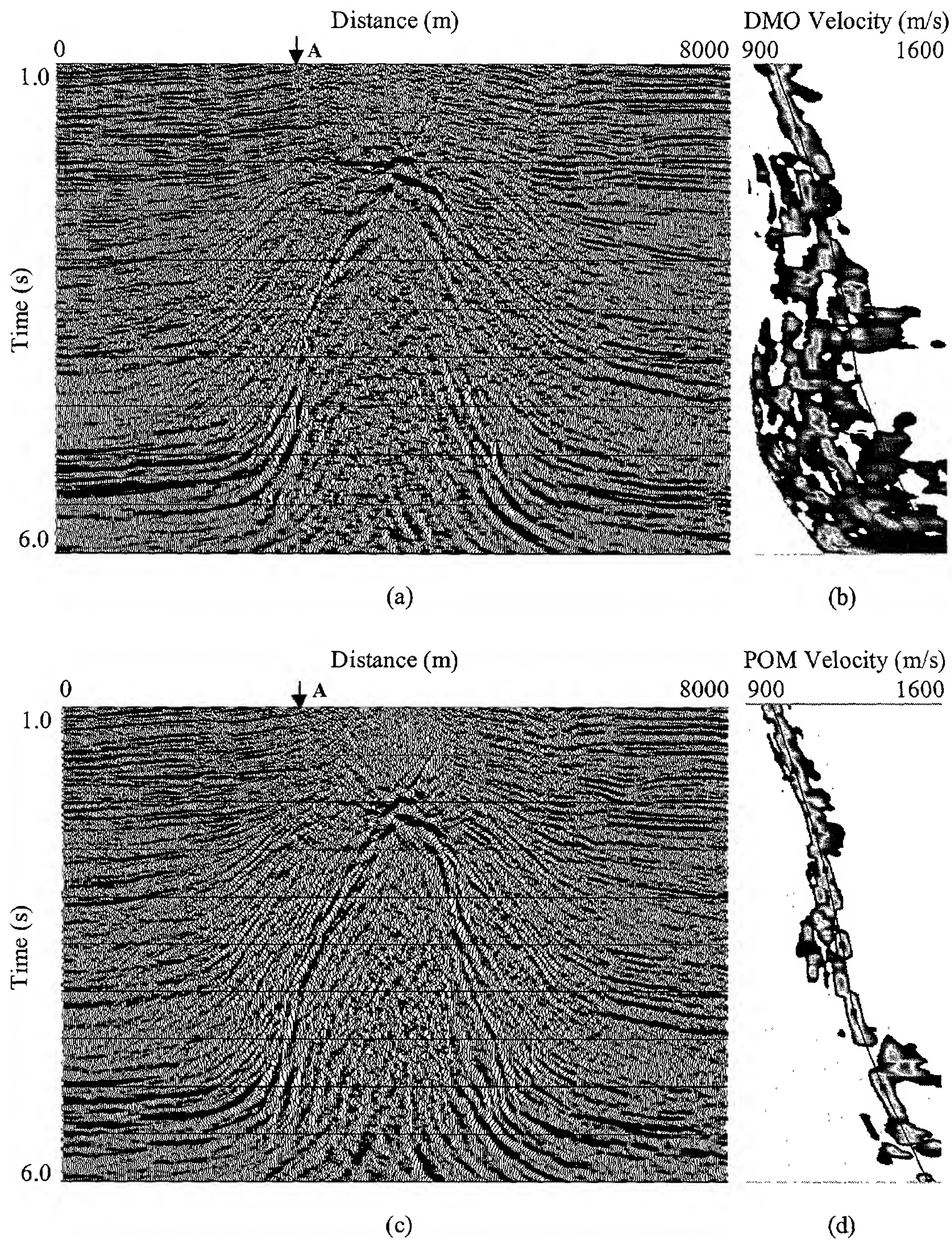

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Fig. 4. Field data example: (a) P-S DMO followed by poststack migration, (b) C-wave DMO velocity spectrum, (c) prestack time migration using POM, and (d) C-wave POM velocity spectrum.

EXHIBIT B:

Converted-wave prestack time migration for isotropic and anisotropic media

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Summary

We present a Kirchhoff prestack time migration technique for converted-waves (C-waves). This technique computes the C-wave diffraction travel time based on the exact travel time equations for v(z) VTI media. We demonstrate that it produces more accurate image than migration algorithms using travel time approximations. For anisotropic media, this technique requires four parameters: C-wave interval velocity v_{Ci}, interval vertical-travel-time ratio γ_{0i}, and Thomsen anisotropic parameters ε_i and δ_i. For isotropic media, only v_{Ci} and γ_{0i} are required for the migration. We use pseudo-offset migration (POM) (Wang and Pham, 2001) to estimate C-wave velocities directly from the C-wave data. We show that C-wave velocity analysis becomes much easier on POM gathers because the positions of dipping events are closer to their true conversion-point positions and conflicting events are reduced after POM.

Introduction

Kirchhoff prestack time migration is often implemented with the hyperbolic travel time approximation, which is strictly correct for a homogeneous constant velocity medium. For multilayered v(z) media or vertical transversely isotropic (VTI) media, more sophisticated travel time equations are needed (Tsvankin and Thomsen, 1994; Li et al., 2001). The three-term approximation in VTI media introduced by Tsvankin and Thomsen (1994) provides sufficient accuracy for P-wave, but for SV-wave (abbreviated to S-wave), the area of validity of approximation is much limited. For C-wave reflection moveout, the three-term approximation can still be accurate up to the offset-to-depth ratio of 2.0 (Thomsen, 1999; Yuan, 2000). C-wave velocity analysis and common-conversion-point (CCP) binning using the three-term travel time approximation can produce accurate results since C-wave data is normally muted at large offset-to-depth ratios. However, for C-wave prestack migration, the travel time approximation is no longer acceptable for imaging high dipping events. The S-wave ray-path is longer than the P-wave ray-path when the scatter point is close to the source location. The migration radius-to-depth ratio could easily be larger than an acceptable level. In this paper, we compute C-wave diffraction travel time using exact travel time equations and show the improved dipping image by comparing with the migration using the three-term approximation of Tsvankin and Thomsen (1994).

Migration parameters that we use for computing the exact travel times are C-wave interval velocity v_{Ci}, interval vertical-travel-time ratio γ_{0i}, and Thomsen (1986) anisotropic parameters ε_i and δ_i. The v_{Ci} is computed from the C-wave short-spread moveout velocity V_{C2} using the Dix formula. The γ_{0i} has to be determined by correlating corresponding P-wave and C-wave events from stacked sections or near-offsets of prestack gathers. This correlation process is also required by CCP binning and NMO correction (Thomsen, 1999). The only difference here is that we need to convert the vertical-travel-time ratio γ_0 to the interval ratio γ_{0i}. The estimation of the anisotropic parameters (Alkhalifah and Tsvankin, 1995; Li and Yuan, 2001) is not addressed in this paper. Our main focus is how to estimate accurate C-wave velocities. A pseudo-offset migration (POM) method (Wang and Pham, 2001) is presented in this paper for this purpose.

Prestack Time Migration with Exact Travel Times

The diffraction travel time at a scatter point in Kirchhoff prestack time migration is the total travel time of P-wave (t_P) down from the source to the scatter point and S-wave (t_S) up from the scatter point to the receiver:

$$t = t_P + t_S \, . \tag{1}$$

For v(z) VTI media, we have the following equations:

$$t_P = \sum_{i=1}^{n} \frac{\Delta t_{P0i}\, v_{P0i} / v_{Pi}(p_P, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}{\sqrt{1 - p_P^2 v_{Pi}^2 (p_P, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}} \, , \tag{2}$$

$$t_S = \sum_{i=1}^{n} \frac{\Delta t_{S0i}\, v_{S0i} / v_{Si}(p_S, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}{\sqrt{1 - p_S^2 v_{Si}^2 (p_S, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}} \, , \tag{3}$$

$$h_P = \sum_{i=1}^{n} \frac{p_P v_{Pi}(p_P, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i) v_{P0i} \Delta t_{P0i}}{\sqrt{1 - p_P^2 v_{Pi}^2 (p_P, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}} \, , \tag{4}$$

$$h_S = \sum_{i=1}^{n} \frac{p_S v_{Si}(p_S, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i) v_{S0i} \Delta t_{S0i}}{\sqrt{1 - p_S^2 v_{Si}^2 (p_S, v_{P0i}, v_{S0i}, \varepsilon_i, \delta_i)}} \, , \tag{5}$$

where h_P and h_S are the horizontal distances from the source / receiver to the scatter point, p_P and p_S are the P- and S-wave ray parameters, Δt_{P0i} and Δt_{S0i} are the vertical-travel-times in the i-th layer, v_{P0i} and v_{S0i} are the vertical velocities of the i-th layer, and v_{Pi} and v_{Si} are the group velocities. Based on the work of Thomsen (1986), we can derive the group velocities as a function of p_P / p_S, v_{P0i}, v_{S0i}, ε_i and δ_i numerically. The ray parameters in equations (2)-(5) are not time-variant, and h_P and h_S are constants for a given scatter point, so we can numerically solve equations (4) and (5) for p_P

and p_S. To compute travel times t_P and t_S, we need to know Δt_{P0i}, Δt_{S0i}, v_{P0i}, v_{S0i}, ε_i, and δ_i. The Δt_{S0i} and v_{S0i} values can not be measured or estimated directly from P- and C-wave data. We replace them by the C-wave vertical-travel-time

$$\Delta t_{C0i} = \Delta t_{P0i} + \Delta t_{S0i}\,, \tag{6}$$

and the interval vertical-travel-time ratio, that is the same as the vertical-velocity-ratio for the i-th layer,

$$\gamma_{0i} = \Delta t_{S0i} / \Delta t_{P0i} = v_{P0i} / v_{S0i}\,. \tag{7}$$

With equations (6) and (7), Δt_{P0i} can also be replaced by Δt_{C0i} and γ_{0i}. The v_{P0i} parameter can be determined from P-wave short-spread moveout velocity v_{P2i}, but the P-wave velocity is indexed at P-wave times and has to be mapped to C-wave times using γ_{0i}. The γ_{0i} parameter is determined by correlating corresponding P-wave and C-wave events from stacked sections or near-offsets of prestack gathers. Thus, it will have some errors. P-wave velocity v_{P2i} often has its own error. If the P-wave velocity error is propagated through γ_{0i} to C-wave migration, it is much difficult to take it out without joint processing of both P- and C-wave data. It is better to use a C-wave velocity to control the C-wave migration. Using the definition of the C-wave interval velocity of Thomsen (1999),

$$v_{Ci}^2 = \frac{v_{P2i}^2}{1+\gamma_{0i}} + \frac{v_{S2i}^2}{1+1/\gamma_{0i}}\,, \tag{8}$$

where

$$v_{P2i}^2 = v_{P0i}^2(1+2\delta_i)\,, \tag{9}$$

$$v_{S2i}^2 = v_{S0i}^2(1+2\sigma_i)\,, \tag{10}$$

$$\sigma_i = \gamma_{0i}^2(\varepsilon_i - \delta_i)\,, \tag{11}$$

we replace v_{P0i} and v_{S0i} with v_{Ci}, γ_{0i}, ε_i and δ_i. Thus the total diffraction travel time can be accurately computed with four parameters v_{Ci}, γ_{0i}, ε_i and δ_i at a given C-wave vertical-travel-time t_{C0}.

In our equations, we do not have γ_{eff} (Thomsen, 1999) which requires to know P-wave velocities. The v(z) effect in travel times is reflected in the interval velocity v_{Ci} and the interval γ_{0i}. The VTI effect is reflected in anisotropic parameters ε_i and δ_i directly. For isotropic v(z) media, equations (2)-(5) can be simplified and the diffraction travel time depends on only two parameters v_{Ci} and γ_{0i} for a given t_{C0}.

Figure 1 shows a synthetic example of C-wave prestack time migration for a single layer VTI model. The Kirchhoff migration with exact travel times computed using equations (1)-(5) is shown in Figure 1b. Comparing with Figure 1c which is the migration with travel time approximation of Tsvankin and Thomsen (1994), the migration with the exact travel times produces well-focused image for the large dipping section.

The exact travel time computation does not increase the migration runtime much since for prestack time migration a small travel time table could be built at each scatter point for all relevant input traces.

Pseudo-Offset Migration

Bancroft et al. (1998) developed the equivalent-offset migration (EOM) method for Kirchhoff prestack summation. Wang and Pham (2001) modified it for converted-wave data by introducing a new offset, called pseudo-offset, and pointed out that migration with pseudo-offset (POM) is less dependent of the initial velocity than EOM. We use POM here to estimate the C-wave velocity for v(z) VTI media.

POM performs the Kirchhoff summation in two steps. The first step is the migration mapping. For each given scatter point D, POM maps each input sample from the survey geometry, defined by the source S and the receiver R in Figure 2, to a new geometry, defined by a pseudo-source S* and a pseudo-receiver R*. There are two conditions the new geometry must be satisfied. 1) The total travel time from S* to D and from D to R* must be equal to the total travel time from S to D and from D to R. 2) The ray from S* to D and from D to R* must have a common ray parameter p. With these two conditions, we can compute the ray parameter p by solving the following equation

$$t_P(p) + t_S(p) = t_P(p_P) + t_S(p_S)\,, \tag{12}$$

and then compute the pseudo-offset, that is defined as

$$x = h_P(p) + h_S(p)\,. \tag{13}$$

The input samples mapped to the same pseudo-offset are accumulated without any time shift so a common-scatter point gather is built with different pseudo-offsets, which is called the POM gather. The second step in POM is the migration stack, which completes the migration by summing the POM gather along the moveout travel times,

$$t = t_P(p) + t_S(p)\,, \tag{14}$$

where p is computed from equation (13) for each given pseudo-offset x. Other parameters used for computing the moveout travel times in equation (14) are v_{Ci}, γ_{0i}, ε_i and δ_i. Assuming γ_{0i}, ε_i and δ_i without errors, the reflection moveout of the plane layers is not altered by the migration mapping even if the initial v_{Ci} may be wrong. Thus, POM gathers can be used to estimate correct v_{Ci} for plane-layered media. Figure 3a shows an example of a POM gather from a flat section in the VTI model of Figure 1a. The POM gather is created using a wrong initial velocity at 2000 m/s and is then corrected with correct model parameters. The flattened event in Figure 3a indicates that we can estimate correct model parameters from it even if the initial C-wave velocity is off by almost 30%. However, the direct inversion of C-wave

interval velocity v_{Ci} using the moveout equation (14) is difficult. One can use the following approximation to scan for the C-wave short-spread moveout velocity V_{C2} (Thomsen, 1999; Li and Yuan, 2001):

$$t^2 = t_{C0}^2 + \frac{x^2}{V_{C2}^2}\left(1 - \frac{Ax^2}{t_{C0}^2 + Ax^2 / \left(1 - 1/\gamma_0\right)}\right),\ A = \frac{(\gamma_0 - 1)^2}{4\gamma_0 V_{C2}^2}, \tag{15}$$

and then compute v_{Ci} using Dix formula. Figure 3b shows that the moveout correction using equation (15) is acceptable only in a limited offset range. Equation (15) is an approximation for a single-layered isotropic medium. To improve its accuracy for velocity analysis of v(z) VTI media, we suggest to compute the residual moveout between equation (14) and (15) using the initial parameters, correct POM gathers with the residuals, and then scan POM gathers with equation (15) for correct velocity V_{C2}. Figure 3c shows that this procedure can produce almost an identical result as the exact travel time equation (14).

Figure 4c shows a field data example of isotropic C-wave prestack time migration using POM. Comparing with C-wave DMO plus poststack migration (Harrison, 1992) (Figure 4a), Figure 4c is well focused around the salt dome. Figure 4b shows a C-wave velocity spectrum after C-wave DMO at the location A marked on Figure 4a. Figure 4d is the corresponding velocity spectrum after POM. Velocity analysis is much easier using Figure 4d than using Figure 4b since the energy is well focused and is at the migrated position after POM.

Conclusions

Travel time computation must be accurate enough for imaging high dipping events of converted-wave data. We derive the exact travel time equations for v(z) VTI media using four parameters: v_{Ci}, γ_{0i}, ε_i, and δ_i. We present pseudo-offset migration to perform Kirchhoff prestack summation and C-wave velocity analysis. We demonstrate that even if the initial velocity is wrong, POM gathers still preserve correct moveout for estimation of C-wave velocities of flat layers. For complex structures, C-wave velocity analysis on POM gathers is much easier than on CCP or DMO gathers.

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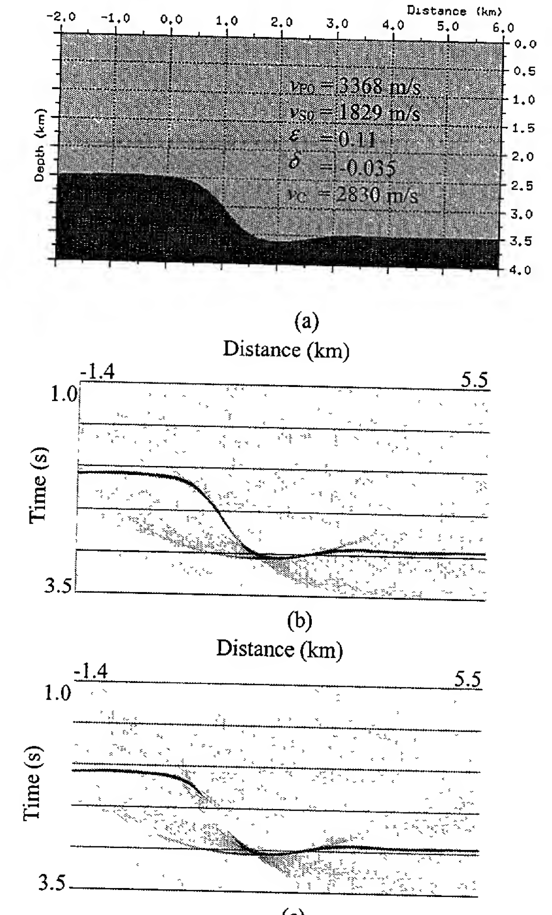

Fig. 1. Converted-wave prestack time migration of a VTI model. (a) VTI model of Taylor sandstone. (b) Migration with exact travel times. (c) Migration with travel time approximation.

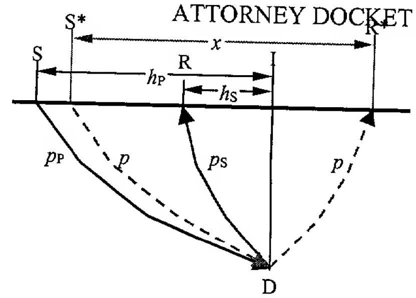

Fig. 2. Geometry of pseudo-offset x

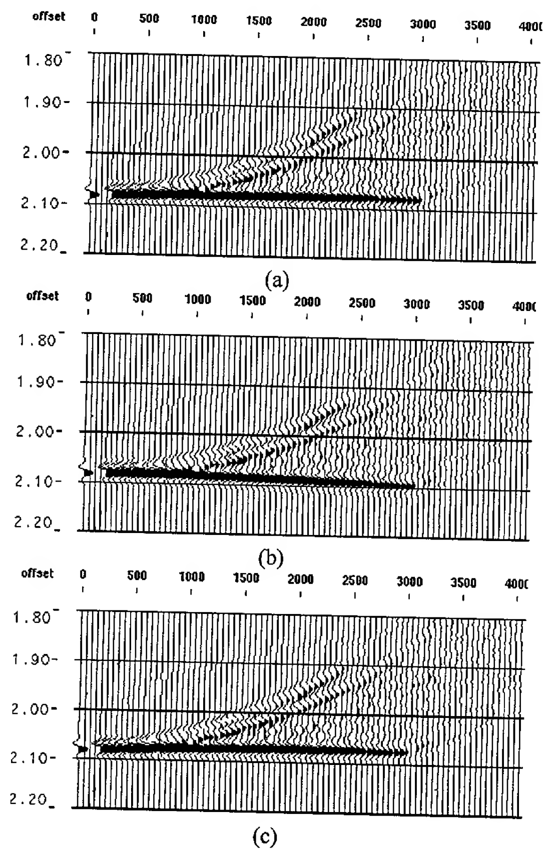

Fig. 3. Moveout corrected POM gathers with the correct C-wave velocity (2830 m/s) for the Taylor sandstone model. The initial velocity used in migration is wrong at 2000 m/s. The travel time equations used for moveout correction are (a) the exact moveout equation (14), (b) approximation equation (15), and (c) equation (15) but with residual moveout correction using the initial velocity.

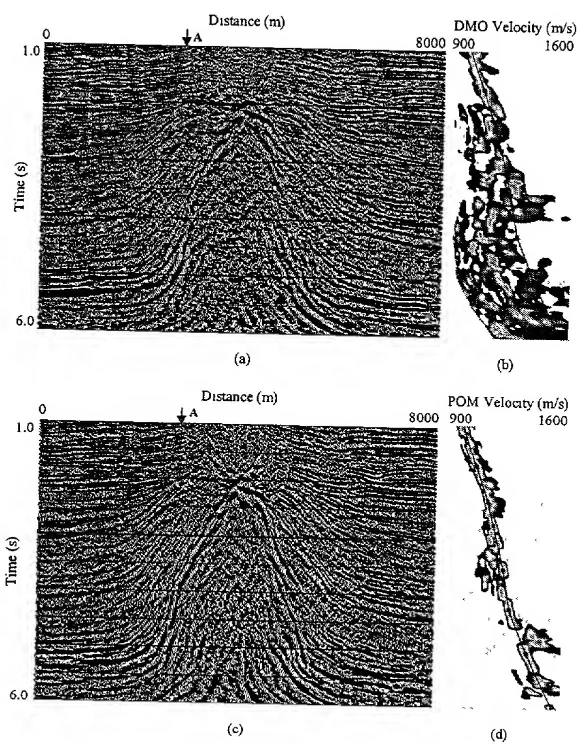

Fig. 4. Field data example: (a) DMO followed by poststack migration, (b) C-wave DMO spectrum, (c) prestack time migration using POM, and (d) C-wave POM velocity spectrum.